A Survey on Carrier Frequency Offset Estimation in OFDM Systems

[1]**Ankita Vyas** [2]**BrajlataChourasiya**
[1]**Research Scholar, M. Tech.** [2]**Assistant Professor**
[1,2]**Dept. of ECE, GGITS, Jabalpur**

Abstract-This paper mainly presents a survey on the various techniques for carrier frequency offset (CFO) estimation in orthogonal frequency division multiplexing (OFDM) over frequency selective fading channel & AWGN. The performance of OFDM system is much sensitive to CFO, which causes inter-carrier interference (ICI). In cyclic prefix (CP) based estimation, the CFO can be estimated from the phase angle of the product of CP and corresponding end part of the OFDM symbol. In CFO estimation using training symbol, the CFO estimation range can be increased by reducing the distance between two blocks of samples for correlation. This was made possible by using training symbol that are repetitive with shorter period. Bit Error Rate vs Signal to Noise Ratio & mean square error (MSE) are the some characterization parameters of the system to observe the effects of frequency offset synchronization.

Keywords- Orthogonal Frequency Division Multiplexing (OFDM), Carrier Frequency Offset (CFO), Inter-Carrier Interference (ICI).

1. INTRODUCTION

OFDM system is widely used in multi-carrier modulation schemes. In this modulation all sub-carriers are orthogonal to each other, which increases the bandwidth efficiency of the system. OFDM transmission frequency channel converts in the group of narrow band flat fading channel, one channel across each sub-channel. OFDM modulation and de-modulation is implemented efficiently by inverse discrete Fourier transform and discrete Fourier transform at the transmitter and receiver respectively [1]. Cyclic prefix (CP) is used for extension of OFDM symbol in time domain which increases the robustness of OFDM system against inter symbol interference (ISI). OFDM has been used in great extent application like wireless local area network IEEE802.11a/g standard, wireless metropolitan network, digital audio broadcasting and terrestrial video broadcasting   standard.
OFDM is very sensitive to time and frequency synchronization. The synchronization problem consists of two major parts: carrier frequency offset (CFO) and symbol time offset (STO). This is due to Doppler shift and a mismatch between the local oscillator at the transmitter and receiver. In STO, time domain δ sample and phase shift offset is affected in the frequency domain. Frequency synchronization error destroys the orthogonality among the sub carriers which causes inter carrier interference (ICI) [2]. Therefore the CFO synchronization is essential to OFDM system. The CFO estimation hasbeen extensively investigated for single input single output(SISO) and for multiple input multiple output (MIMO) OFDM based system. The normalized CFO can be divided into two parts which are integral CFO (IFO) $\xi_i$and fractional CFO (FFO) ξ_f. IFO produce a cyclic shift by $\xi_i$in receiver side to corresponding sub carrier it does not destroy orthogonality among the sub carrier frequency component and FFO destroysthe orthogonality   between   the   sub   carriers.
For CFO estimation in time domain, cyclic prefix (CP) and training sequence are used. CP based estimation has analyzedassuming negligible channel effect. CFO can be found fromthe phase angle of the product of CP and the correspondingpart of an OFDM symbol, the average has taken over the CPintervals and

in training sequence estimation using trainingsymbol that is repetitive with some shorter period.
The orthogonality of the OFDM relies on the condition that transmitter and receiver operate with exactly the same frequency reference. If this is not the case, the perfect orthogonality of the subcarrier will be lost, which can result to subcarrier leakage, this phenomenon is also known as the Inter Carrier Interference (ICI) [1]. In another word, the OFDM systems are sensitive to the frequency synchronization errors in form of CFO. CFO can lead to the Inter Carrier Interference (ICI); therefore CFO plays a key role in Frequency synchronization. Basically for getting a good performance of OFDM, the CFO should be estimated and compensated. Lack of the synchronization of the local oscillator signal (L.OSC); for down conversion in the receiver with the carrier signal contained in the received signal causes Carrier Frequency Offset (CFO) which can create the following factors:

(i) Frequency mismatched in the transmitter and the receiver oscillator
(ii) Inter Carrier Interference (ICI)
(iii) Doppler Effect (DE).

2. LITERATURE SURVEY

[1] Dajin Wang et-al, "An Approximate Method of Carrier Frequency Offset (CFO) Estimation for OFDM System", IEEE 80th Vehicular Technology Conference (VTC Fall), Vancouver, 2014.

In this paper the problem of carrier frequency offset (CFO) estimation for orthogonal frequency division multiplexing (OFDM) systems. An approximated method for CFO estimation is derived. They show that the introduction of CFO can be taken as the result of passing through a frequency domain filter, whose coefficients are functions of CFO. To estimate the CFO, we construct an estimator based on the filter coefficients. In this way, the CFO estimation problem is converted to filter coefficients estimation. They develop a fast algorithm with lower computational complexity. Results shows that this method is effective for channel with large Doppler spread.

[2] Tzu-Chiao Lin et-al, "A Low-Complexity Blind CFO Estimation for OFDM Systems", IEEE International Conference on Acoustic, Speech & Signal Processing (ICASSP), Pp. 8083 – 8086, Florence, 2014.

The estimation of carrier frequency offset (CFO)is an important issue in the study of the orthogonal frequencydivision multiplexing (OFDM) systems. In the past, many CFOestimation methods have been proposed. In this paper, they proposed a new blind CFO estimation for OFDM systems based on theso-called remodulated received vectors [8]. The CFO estimateis given by a closed form formula. The proposed method hasvery low complexity and its performance is robust to differentmodulation symbols and the presence of virtual carriers.

[3]Yufei Jiang et-al, "Semi-Blind MIMO OFDM Systems with Precoding Aided CFO Estimation and ICA Based Equalization",

Signal Processing for Communications Symposium, Globecom , Pp. 3499 – 3503, Atlanta, 2013.

In this paper, authors gave a semi-blind multiple-input multipleoutput (MIMO) orthogonal frequency division multiplexing(OFDM) system, with a precoding aided carrier frequencyoffset (CFO) estimation approach, and an independent component analysis (ICA) based equalization structure. A numberof reference data sequences are carefully designed offline andare superimposed to source data via a non-redundant linearprecoding process, which can kill two birds with one stone,without introducing any extra total transmit power and spectraloverhead. First, the reference data sequences are selected froma pool of carefully designed orthogonal sequences. The CFOestimation is to minimize the sum cross-correlation between theCFO compensated signals and the rest orthogonal sequences inthe pool. Second, the same reference data enable elimination ofthe permutation and quadrant ambiguity in the ICA equalizedsignals by maximizing the cross-correlation between the ICAequalized signals and the reference data. Simulation results showthat, without extra bandwidth and power needed, the proposedsemi-blind system achieves a bit error rate (BER) performanceclose to the ideal case with perfect channel state information(CSI) and no CFO. Also, the precoding aided CFO estimation outperforms the constant amplitude zero autocorrelation(CAZAC) sequences based CFO estimation approach, with nospectral overhead.

[4] P. Malarvezhi et-al, "A Modified Preamble structure based Carrier Frequency Offset (CFO) and Phase noise compensation in an OFDM system", IEEE International Conference on Emerging Trends in Computing, Communication & Nanotechnology (ICECCN), Pp. 13 – 18, Tirunelveli, 2013.

The Systems using Orthogonal Frequency DivisionMultiplexing (OFDM) suffer with carrier frequency offset (CFO)and phase noise which results in inter carrier interference (ICI)due to which there will be large performance degradation. Theimpairments like CFO and phase noise are caused due tomismatch of carrier frequency at the transmitter to localoscillator frequency at the receiver, multipath and Doppler shift.This paper presents a modified preamble structure basedapproach for CFO and phase noise compensation in an OFDMsystems which mitigate the effect of inter carrier interference andits equivalent energy loss. Theoretical analysis and simulationresults substantiate the importance and advantages of proposedCFO and phase noise compensation approach. This proposedmethod provides a considerable signal to noise ratio gain on biterror rate performance

[5] S. Kumarapandian et-al, "Performance analysis of CFO mitigation algorithms in Asynchronous Cooperative OFDM Communication system", 2nd IEEE International Conference on Sustainable Energy & Intelligent System (SEISCON), Pp. 632-637, Chennai, 2011.

In this paper, authors analyzed the non-cooperative Orthogonal Frequency Division Multiplexing (OFDM) and Cooperative-OFDMcommunication system by comparing their performances. Carrierfrequency offset (CFO) mitigation is critical for OFDM based cooperative transmissions because even small CFO per transmittermay lead to severe performance loss, especially when the numberof cooperative transmitters is large. They showed that cyclic prefix (CP) can be exploited to mitigate or even remove completelythe CFO. The mitigation performance increases along with theCP length. In particular, long CP with length proportional to N*I,where N is the Fast Fourier Transform (FFT) block length and I isthe number of cooperative transmitters, can guarantee a completeCFO removal. While this comes with a reduction in bandwidth efficiency, the long CP in the proposed scheme is exploited to enhance transmission power efficiency in a way similar to spread-spectrumsystems, and thus is different from conventional CP that degradesboth bandwidth and power efficiency. Authors showed that howperformance of mitigation algorithm vary with cyclic prefix lengthand performance evaluation in case of error up in the estimation ofcarrier frequency offset (CFO).Comparing the

performance of thismitigation algorithm with Orthogonal Frequency Division MultipleAccess (OFDMA) mitigation algorithm for different carrier frequency offset values.

3. EFFECTS OF FREQUENCY OFFSET ON OFDM SIGNALS

When CFO happens, it causes the receiver signal to beshifted in frequency (δf); this is illustrated in the figure 1.If the frequency error is an integer multipleI ofsubcarrier spacing δf, then the received frequency domainsubcarriers are shifted byδf x I .

Figure 1: Frequency Offset

On the other hand, as we know the subcarriers (SCs) will sample at their peak, and this can only occur when there is no frequency offset, however if there is any frequency offset, the sampling will be done at the offset point, which is not the peak point. This causes to reduce the amplitude of the anticipated subcarriers, which can result to raise the Inter Carrier Interference (ICI) from the adjacent subcarriers (SCs). Figure 2 shows the impact of carrier frequency offset (CFO). It is necessary to mention that although it is true that the frequency errors typically arise from a mismatch between the reference frequencies of the transmitter and the receiver local oscillators, but this difference is avoidable due to the tolerance that electronics elements have.
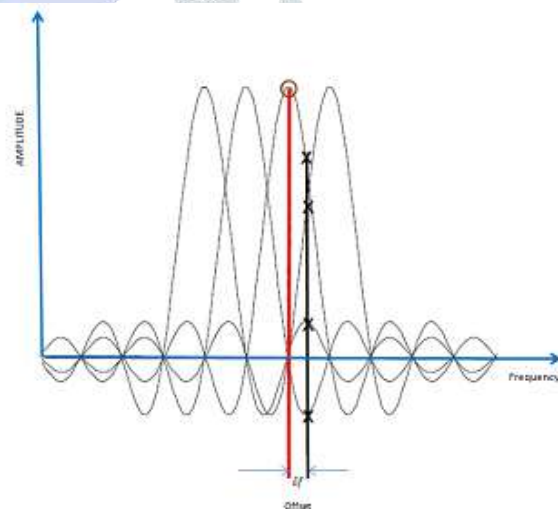

Figure 2: Frequency Offset

Therefore there is always a difference between the carrier frequencies that is generated in the receiver with the one that is generated in transmitter; this difference is called frequency offset f_{offset} i.e.

$$f_{offset} = f_c - f'_c$$

In where f_c is the carrier frequency in the transmitter and f'_c is the carrier frequency in receiver.

4. CARRIER FREQUENCY OFFSET (CFO)

The OFDM systems are very sensitive to the carrier

frequency offset (CFO) and timing, therefore, before demodulating the OFDM signals at the receiver side, the receiver must be synchronized to the time frame and carrier frequency which has been transmitted. Of course, In order to help the synchronization, the signals that are transmitted, have the references parameters that are used in receiver for synchronization. However, in order the receiver to be synchronized with the transmitter, it needs to know two important factors:

(i) Prior to the FFT process, where it should start sampling the incoming OFDM symbol from.

(ii) How to estimate and correct any carrier frequency offset (CFO).

4.1 SOURCES OF FREQUENCY OFFSET

A few other sources can cause frequency offset, such as frequency drifts in transmitter and receiver oscillators, Doppler shift, radio propagation and the tolerance that electronics elements have in local oscillators in transmitter and the receiver. When there is a relative motion between transmitter and receiver the Doppler can happen [4]. It is worth to mention the radio propagation talks about the behavior of radio waves when they are broadcasted from transmitter to receiver. In terms of propagation, the radio waves are generally affected by three phenomena which are: diffraction, scattering and reflection.

4.2 DOPPLER EFFECT

The Doppler Effect (DE) defines as follows:

$$f_d = \frac{v.f_c}{c}$$

In where f_d is Doppler frequency, c is the speed of light, and v is the velocity of the moving receiver. (i.e. 100 km/h). The normalized CFO (ε) is defined as follows:

$$\varepsilon = \frac{f_{offset}}{\Delta f}$$

In where Δf is the subcarrier spacing, it is necessary to mention that ε has two parts, one integer (ε_ε) and one fractional ($\varepsilon_\boxempty$) so we have:

$$\varepsilon = \varepsilon_i + \varepsilon_f$$
$$\text{where } \varepsilon_i = \lfloor \varepsilon \rfloor$$

5. SYSTEM MODEL

In OFDM transmission scheme a wide-band channel divided into N orthogonal narrow-band sub-channels. N Point IFFT and FFT are used to implement OFDM Modulation and Demodulation. The transmitter maps the message bits X_m intoa sequence of BPSK or QAM symbols which are subsequentlyconverted into an N parallel bit stream. Each of N symbolsfrom the serial-to-parallel (S/P) conversion is modulated onthe different sub-carriers.
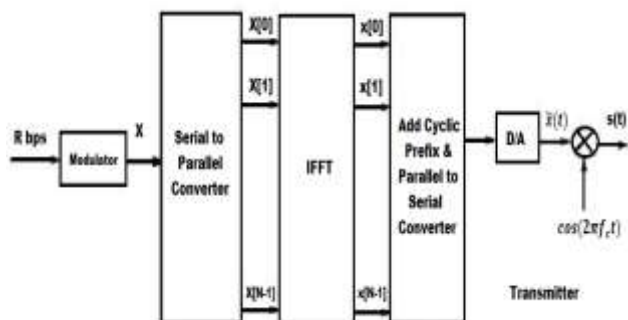
Figure 3: OFDM Transmitter block
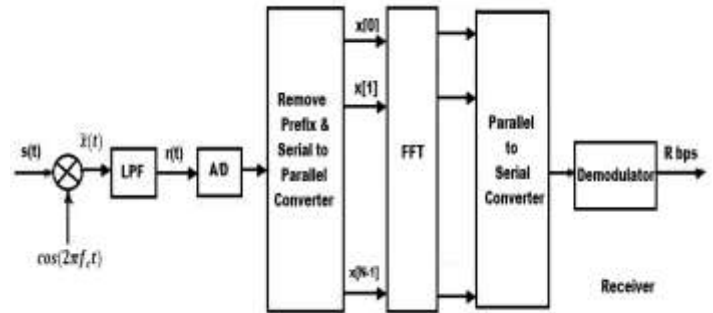
Figure 4: OFDM Receiver block

IFFT of $s(t)$ will be;

$$x(n) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X(i) e^{\frac{j2\pi n i}{N}}, \qquad 0 \le n \le N-1$$

6. CFO ESTIMATION ALGORITHM &TECHNIQUES

CFO can produce Inter Carrier Interference (ICI) which can be much worse than the effect of noise on OFDM systems. That's why various CFO estimation and compensation algorithms have been proposed. For showing the importance of it, it is enough to mention that, by now the researchers have proposed numerous and various CFO estimation and compensation techniques and algorithms, which these methods can generally be categorized into two major branches:

1. Training based algorithm
2. Blind algorithm and Semi-blind algorithm

6.1 TRAINING BASED ALGORITHM

The training sequence can be designed the way that canlimit the number of computation at the receiver side;therefore in general, these algorithms have a lowcomputational complexity. On the other hand, thenegative point of training based algorithm is the trainingsequences that must be transmitted from transmitter duringits transmission. This can cause the reduction of theeffectiveness of the data throughput.

6.2 BLIND AND SEMI-BLIND ALGORITHMS

Another algorithm that has been used is called Blind CFO estimation algorithm. In these algorithms by using the statistical properties of the received signal, the CFO will be estimated. Since the receiver doesn't have any knowledge of the signal that the transmitter has been sending, therefore the blind algorithms are considered to have a high computational complexity. The high computational complexity is the disadvantage of these algorithms. In compared with training based algorithm, blind algorithms have no need to the training sequences; therefore there is no training overhead for these algorithms. Further CFO estimation techniques can be subdivided in four major categories are as:

*A. CP Based:*With perfect symbol synchronization, a CFO of ξ results in a phase rotation of $2\pi n\xi/N$ in the received signal. Under the assumption of negligible channel effect, the phase difference between CP and the corresponding rear part of an OFDM symbol (spaced N samples apart) is $2\pi N\xi/N = 2\pi\xi$. Then, the CFO can be found from the phase angle of the product of CP and the corresponding rear part of an OFDM symbol, CFO estimation using CP based.

$$\tilde{\xi} = (1/2\pi) arg \{y_l^*[n]y_l[n+N]\}$$

n = -1, -2, ... -N_g. In order to reduce the noise effect, its average can be taken over the samples in a CP interval.

$$\tilde{\xi} = (1/2\pi)arg\left\{\sum_{n=-N_g}^{-1} y_l^*[n]y_l[n+N]\right\}$$

Arg() performed $tan^{-1}()$, the range of the CFO estimation is [-0.5+0.5] and mean square error performed by $\overline{\tilde{\xi} - \xi}$.

B. Symbol Based: Two identical training symbols are transmitted consecutively and the corresponding signals with CFO of ξ are related with each other. For an OFDM transmission symbol at one receiver with an assumption of the absence of noise the 2N Point sequence is [14].

$$r_n = \frac{1}{N}\sum_{k=0}^{N-1} H_k X_k e^{2\pi j(k+\xi)/N}$$

n = 0, 1, ... 2N-1, The k_{th} element of the N Point DFT of the first N points for the above equation is;

$$R_{1k} = \sum_{n=0}^{N-1} r_n e^{-2\pi jkn/N}$$

k = 0, 1, 2, ... N-1,
The second half of the sequence is;

$$R_{2k} = \sum_{n=0}^{N-1} r_n + N e^{-2\pi jkn/N}$$

$r_n + N = r_n e^{2\pi j\xi}, R_{2k} = R_{1k}e^{2\pi j\xi},$ including the AWGN noise, $Y_{1k} = R_{1k} + W_{1k}$ &

$Y_{2k} = R_{1k}e^{2\pi j\xi} + W_{2k}$; k = 0, 1, 2, ... N-1.
Observe that between the first and second DFT symbols, both ICI and signal are altered in exactly the same way, by a phase shift proportional to frequency offset. Therefore, if frequency offset ξ is estimated using above observations, it is possible to obtain accurate estimation even when the offset is too large for satisfactory data demodulation [14].

$$\tilde{\xi} = \left(\frac{1}{2\pi}\right)tan^{-1}\left\{\frac{\sum_{k=0}^{N-1} Im[Y_{2k}Y_{1k}^*]}{\sum_{k=0}^{N-1} Re[Y_{2k}Y_{1k}^*]}\right\}$$

The limit for accurate estimation by $/\xi| \le 0.5$.

C. Training Sequence Based: CFO only within the range $/\xi| \le 0.5$, Since CFO can be large at initial synchronization stage, we may need estimation techniques that can cover wider CFO range. The range of CFO estimation can be increased by reducing the distance between two blocks of samples for correlation. This is made possible by using training symbols that are repetitive with some shorter period. Let D represents the ratio of the OFDM symbol length to the length of a repetitive pattern. Let the transmitter sends the training symbols with D repetitive patterns in the time domain, which generated combo-type signal in the frequency domain after taking IFFT.

$$X_l[k] = \begin{cases} A_m & if, k = D.i, i = 0, 1, ...(N/D-1) \\ 0 & eleswhere \end{cases}$$

Where, A_m represents an M-ary symbol and N/D is an integer and $x_l[n]$ and $X_l[n+N/D]$ are identical. After receiving repetitive length data sequence, receiver can make CFO estimation as [16];

$$\tilde{\xi} = (D/2\pi)arg\left\{\sum_{n=0}^{N/D} y_l^*[n]y_l[n+N/D]\right\}$$

The estimation range in this technique is $/\xi| \le D/2$, which becomes wider as D increases and number of samples for the computation of correlation is reduced by 1/D, which degrade the MSE performance of OFDM system. In other words, the

increase in estimation range is obtained at the sacrifice of MSE (mean square error) performance.

$$\tilde{\xi} = (D/2\pi)arg\left\{\sum_{m=0}^{D-2}\sum_{n=0}^{N/D-1} y_l^*[n+mN/D]y_l[n+(m+1)N/D]\right\}$$

The MSE performance can be improved without reducing the estimation range of CFO by taking the average of the estimates with the repetitive patterns of the shorter period.

D. Pilot Based: Pilot tones inserted in the frequency domain and transmit every OFDM symbol for CFO tracking. The signals are transformed into $Y_l[k]$ $_{Nk=0-1}$ and $Y_{l+D}[k]$ $_{Nk=0-1}$ though FFT, from which pilot tones are extracted. After estimating CFO from pilot tones in the frequency domain, the signal is compensated with the estimated CFO in the time domain. In this process, two different estimation modes for CFO estimation are implemented: acquisition and tracking modes. In the acquisition mode, a large range of CFO including an integer CFO is estimated and in the tracking mode, only fine CFO is estimated. The integer CFO is estimated by [15].

$$\tilde{\xi} = \left(\frac{1}{2\pi T_{sub}}\right)max(\xi)\left\{|\sum_{j=0}^{L-1} Y_{l+D}[p[j],\right.$$

$$\xi]Y_l^*[p[j],\xi]X_{l+D}^*[p[j]]X_l[p[j]]|\bigg\}$$

where L, p[j], and $X_l[p[j]]$ denote the number of pilot tones, location of the j_{th} pilot tone, and the pilot tone located at p[j] in the frequency domain at the l_{th} symbol period [3].

7. CONCLUSION

CFO estimation is done by using four different techniques, one by using the phase difference between CP and the corresponding rear part of an OFDM symbol. Second by using the phase difference between two repetitive preambles. Third by using, training sequence with D integer i.e. ratio of the OFDM symbol length to the length of a repetitive pattern. Fourth one by estimation between pilots tones in two consecutive OFDM symbols. In all of the techniques we can categorized these into 3 major classes, data driven, blind and semi-blind.
Typically, three types of algorithms are used for frequency synchronization: algorithms that use pilot tones for estimation (data-aided), algorithms that process the data at the receiver (blind), and algorithms that use the cyclic prefix for estimation [5]. Among these algorithms, blind techniques are attractive because they do not waste bandwidth to transmit pilot tones [4]. However, they use less information at the expense of added complexity and degraded performance [4]. The general approaches to the problem of synchronization consist of a number of steps, including frame detection, carrier frequency offset and sampling error correction [7]. Frame detection is used to determine the symbol boundary needed for correct demodulation. Within each frame, the carrier frequency offset between the transmitter and the receiver causes an unknown phase shift factor [7]. Also we conclude that if a semi-blind technique is used which is having advantages of data-aided method and at the same time use of CP, this hybrid approach can be implemented and tested.

8. REFERENCES

[1] Dajin Wang et-al, "An Approximate Method of Carrier Frequency Offset (CFO) Estimation for OFDM System", IEEE 80th Vehicular Technology Conference (VTC Fall), Vancouver, 2014.
[2] Tzu-Chiao Lin et-al, "A Low-Complexity Blind CFO Estimation for OFDM Systems", IEEE International Conference

on Acoustic, Speech & Signal Processing (ICASSP), Pp. 8083 – 8086, Florence, 2014.

[3] Yufei Jiang et-al, "Semi-Blind MIMO OFDM Systems with Precoding Aided CFO Estimation and ICA Based Equalization", Signal Processing for Communications Symposium, Globecom , Pp. 3499 – 3503, Atlanta, 2013.

[4] P. Malarvezhi et-al, "A Modified Preamble structure based Carrier Frequency Offset (CFO) and Phase noise compensation in an OFDM system", IEEE International Conference on Emerging Trends in Computing, Communication & Nanotechnology (ICECCN), Pp. 13 – 18, Tirunelveli, 2013.

[5] S. Kumarapandian et-al, "Performance analysis of CFO mitigation algorithms in Asynchronous Cooperative OFDM Communication system", 2nd IEEE International Conference on Sustainable Energy & Intelligent System (SEISCON), Pp. 632-637, Chennai, 2011.

[6] ChiSung Bae and Dong Ho Cho, 'Fairness-Aware Adaptive Resource Allocation Scheme in Multihop OFDMA Systems', IEEE Communications Letters, Vol. 11, pp.134-136, 2007.

[7] Ernest S.L., Vincent K.N., Roger S.C. and Ross D.M., 'Adaptive Resource Allocation and Capacity Comparison of Downlink Multiuser MIMO-MC-CDMA and MIMO-OFDMA', IEEE Transactions on Wireless Communications, Vol. 6, pp. 1083 -1093, 2007.

[8] HassenKaraa., Raviraj S.A. and Adam J.T., 'Linear Precoding for Multiuser MIMO-OFDM Systems', IEEE International Conference on Communications, pp. 2797-2802, 2007.

[9] Gao X. and Araghi Pour M., 'Computationally Efficient Resource Allocation for Multiuser OFDM Systems', Proceedings of the IEEE Wirless Communication and Networking Conference, (WCNC2006), Vol. 2, pp. 804-809, 2006.

[10] Jung Won Lee, Hui-Ling Lou and John M.C., 'SNR analysis of OFDM system in the presence of carrier frequency offset for fading channels', IEEE Transactions on wireless communications, Vol. 5, No. 12, 2006.

[11] Jian Xu, Jongkyung Kim, Wonkyu Paik and Jong-Soo Seo, 'Adaptive Resource Allocation Algorithm with Fairness for MIMOOFDMA System', Proc. VTC- IEEE, Vol. 4, pp. 1585-1589, 2006.

[12] Chengkang Pan., YuemingCai and Youyun Xu, 'Adaptive Subcarrier and Power Allocation for Multiuser MIMO-OFDM Systems', IEEE International Conference on Communications, Vol. 4, pp. 2631 – 2635, 2005.

[13] Jiang T., Yang Y. and Song Y H., 'Exponential companding techniques for PAPR reduction in OFDM systems', IEEE Trans. Broadcast, Vol. 51, No. 2, pp. 244-248, 2005.

[14] Jiang T. and Zhu G. (2004), 'Nonlinear companding transform for reducing peak-to-average power ratio of OFDM signals', IEEE Trans. Broadcast., Vol. 50, pp. 342-346, 2004.

[15] Guodong Zhang, 'Subcarrier and Bit Allocation for Real-time Services in Multiuser OFDM Systems', IEEE International Conference on Communications, Vol. 5, pp. 2985-2989, 2004.

[16] Hanzo L., Munster M., Choi B J. and Keller T.,'OFDM& MC CDMA for broadband Multi-User Communications, WLANs and Broadcasting', ISBN 0-470-85879-6, 2004.

[17] Jang J. and Lee K.B. (2003), 'Transmit Power Adaptation for Multiuser OFDM Systems', IEEE Journal on Selected Areas in Communications, Vol. 21, No. 2, pp. 171 -178, 2003.

[18] Jiho Jang, Kwang Bok Lee and Yong-Hwan Lee, 'Transmit Power and Bit Allocations for OFDM Systems in a Fading Channel', Proc. IEEE GlobalCommunications Conference Vol. 2, pp.858-862, 2003.

[19] Caire G. and Shamai S., 'On the achievable throughput of a multiantenna Gaussian broadcast channel', IEEE Transactions on Information Theory, Vol. 49, No. 7, pp. 1691 -1706, 2003.

[20] Bolcskei H., Gesbert D. and Paulraj A., 'On the capacity of OFDM based spatial multiplexing systems', IEEE Trans. On Communications, Vol. 50, No. 2, pp. 225-234, 2002.

[21] Chung S.T. and Goldsmith A. J., 'Degrees of freedom in adaptive modulation: a unified view', IEEE Trans. on Comm, Vol. 49, pp. 1561 -1571, 2001.

[22] Hui Liu and Guoqing Li (2000) 'OFDM-Based Broadband Wireless Networks', ISBN-1 3 978-0-471 -72346-2, 2000.

[23] Keller and Hanzo L., 'Adaptive multicarrier modulation: a convenient framework for time-frequency processing in wireless communications', Proc. of the IEEE, Vol. 88, pp. 611 -640, 2000.

[24] Lawrey E. (1999), 'Multiuser OFDM', in Proc. International Symposium on Signal Processing and its Applications, pp. 761 -764, 1999.

[25] Cheong Yui Wong and Roger S.C., 'Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation', IEEE Journal on Selected Areas in Communications, Vol. 17, pp. 1747-1758, 1999.

[26] Leke A. and Cioffi J.M., 'Multicarrier systems with imperfect channel knowledge,' Proc. PIMRC, pp. 549-553, 1998.

[27] Li X and Cimini L J., 'Effects of clipping and filtering on the performance of OFDM', in Proc. Globecom., pp. 1634-1638, 1997.

[28] Beek J.J., Sandell M. and Borjesson P.O. , 'ML estimation of time and frequency offset in OFDM system', IEEE Transactions on Signal Processing, Vol. 48, pp. 1800-1805,1997.

[29] Moose H. (1994), 'A Technique for Orthogonal Frequency Division Multiplexing Frequency Offset Correction', IEEE Transactions on Comm. Vol. 42, No. 10, 1994.